# Note on the Liquid Crystal Display Industry[1]

In a growing information society, human beings acquire more than 90 percent of their information visually. Individuals are linked to information through a variety of hardware interfaces, including display devices that provide the visual interface between people and such hardware as computers, audio/visual equipment, and a wide range of consumer and industrial machines. In 1992, Japan's production of electronic displays had reached $10 billion. According to *Display Devices* magazine, "Analysts say the world market for electronic displays is about $20 billion. By 1995, it will increase to $30 billion, exceeding $40 billion by 2000."[2]

With the introduction of television in the 1940s, cathode ray tubes (CRTs) were among the first electronic display devices to be commercialized. In the 1960s, CRT displays set the standard for color pictures and alternative technologies had to be competitive with CRT price and quality. By the 1990s, new *flat panel displays* were being introduced to make products lighter and smaller. In 1993, the world market for flat panel displays reached $4.69 billion, according to ETP Corporation, an American inspection company. ETP projected this market to reach $5.09 billion in 1994, and $7.58 billion by 1998.[3] Japanese manufacturers of flat panel displays were even more optimistic. According to Japan's Nikkei Sangyo newspaper, industry survey's projected the total market to reach $5.4 billion in 1994 and $13 billion yen by 1996.

## Display Devices

Cathode ray tubes (CRTs), liquid crystal displays (LCDs), plasma display panels (PDPs), vacuum fluorescent displays (VFDs), electroluminescent (EL) displays, and light-emitting diode (LED) displays all serve as electronic displays. Figure 1 shows the basic requirements for displays. TV and computer display monitors are the main uses for CRTs. CRTs, however, require higher voltages to control the emission and angle of electron beams than other display technologies, and are larger and heavier than other displays. North American demand began shifted from monochrome to color displays in the early 1990s as Windows software became the standard operating systems for PCs.

Japanese produced over 37.27 million CRTs in 1993 with nearly $5.59 billion in sales as shown in Table 1. Smaller 14-inch tubes had fallen from 70 percent to 65 percent of the market and had become very price competitive as South Korean and Taiwanese firms entered the business. Production was expected to reach $2.8 billion in 1994 for 14- and 15-inch CRTs. Both Korean and Taiwanese makers had entered the market and had made remarkable progress in production of 14-inch monitors overseas, and were

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[1]  The development of this case was supported by Keio University's Graduate School of Business Administration.

[2] "Electronic Display Makers Develop Technologies to Improve Quality, Increase Screen Size," *Display Devices '94*, Fall 1994, p. 5.

[3] Ibid.

producing 15-inch and larger models at home. South Korean makers produced 30.2 million 14 and 15 inch tubes in 1993, surpassing Japan's production of 30 million smaller size units. Taiwan was in third place in 1993, producing 13.3 million monitors valued at over $3.2 billion. The Taiwanese government was sponsoring a national effort to develop advanced CRT technologies capable of competing with Japanese manufacturers.

**Figure 1: Functions Required for Different Display Applications**

| Required functions | Sub-note computer | Notebook (high portability) | Notebook (high function) | Laptop | Monitors | Vehicle mounted products | Projectors |
|---|---|---|---|---|---|---|---|
| Low power | ☺ | 😐 | | | | | |
| Thin/light weight | ☺ | 😐 | | | | | |
| Multigray scale | | | 😐 | 😐 | ☺ | | ☺ |
| High brightness | | | 😐 | 😐 | ☺ | ☺ | |
| Wide viewing angle | | | 😐 | 😐 | ☺ | ☺ | |
| High density | | | 😐 | ☺ | ☺ | | 😐 |
| Large screen | | | 😐 | ☺ | ☺ | | |
| Resistance to ambient conditions | | | | | | ☺ | 😐 |

Source: Susumu Ohi, "Development of TFT-LCD and its application to notebook size PCs." Display Devices (Spring 94), p. 25.

**Table 1: CRT market breakdown by size (1993)**

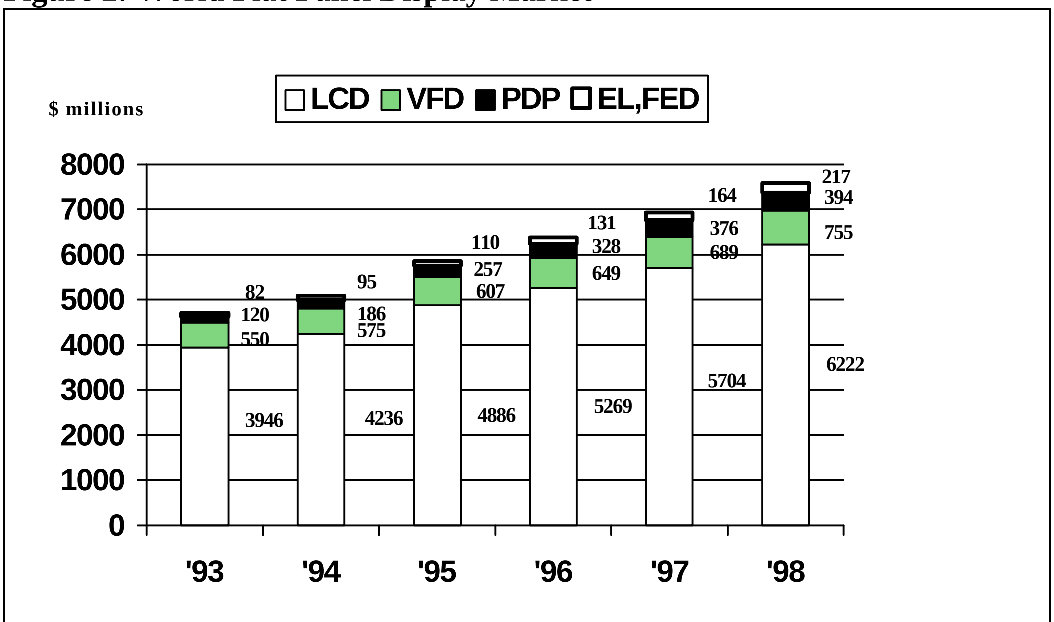
| | | |
|---|---|---|
| 14-inch tubes | 23 million units | 65% |
| 15-inch tubes | 7 million yen | 20% |
| 17-inch tubes | 3 million yen | 9% |
| Others | 4 million yen | 6% |

Source: NEC Corporation.

With the increasing value of the yen, production of CRTs in Japan fell 9.1 percent in 1993. Monochrome CRTs accounted for under one percent of Japanese production. Japanese makers had responded to increased competition by shifting production to Southeast Asia, and by producing 15-inch and 17-inch color CRTs in response to the increased demand for large-size PC displays. Japanese firms like Sony, Hitachi, Matsushita, NEC, Toshiba and Mitsubishi were using their leading technologies to offer larger screen products with advanced features. High precision models used for computer displays reached 18 million units, or $2.94 billion.[4] According to value, about 44 percent of these CRTs were adopted for TVs and about 52 percent for displays. Energy consumption, size and weight were major weaknesses of CRTs. With personal computers accounting for five percent of total energy consumption in the United States, power reduction had become a major development effort for Japanese CRT makers.

As substitutes for CRTs, *flat panel display* systems were candidates for replacing CRTs, including LEDs, EL panels, VFDs, PDPs and LCDs. As shown in Figure 2, flat panel display technologies provided greater compactness (they are thinner), energy efficiency (they require lower voltage and lower power consumption) and greater diversity of applications than CRT displays. Figure 3 compares flat panel display technologies. If semiconductors are equivalent to Japanese rice, then flat panel displays such as LCDs are a new strain of rice that are indispensable to Japan's sustained economic growth. LCDs were considered the second semiconductor industry and were expected to sustain Japan's prominence in hi-tech products into the 21st century.

**Figure 2: World Flat Panel Display Market**




Source: ETP Corporation

Plasma displays (PDPs) reached $186 million in 1994. They are thinner and lighter than CRTs, and can be used for 20-inch and larger displays. While plasma displays are more expensive than CRTs, they offered excellent image quality. PDPs feature self-emission, brightness, and excellent visibility, and have superb contrast, rapid response, and a wide angle of visibility. Neon gas, sealed within glass cathode, is lighted when either AC or DC voltages are applied across the anode. This made them especially applicable for

[4] Op. cit.

automobile use. Early applications included electronic cash registers, point-of-sale terminals, and stock price display boards. They began use in laptop computers nearly ten years ago, and today are being applied to factory automation equipment, automatic ticket vending machines, and measuring instrument display systems. The Japan Broadcasting Corporation (NHK) has adopted plasma displays for large, color high definition monitors with aspect ratios of 16:9. With improved speed, NHK hopes to develop a monitor larger than 70 inches. While Fujitsu was a leader in plasma display production, Oki, Matsushita, and Mitsubishi have all experimented with producing high definition plasma displays. They had introduced 21-inch color plasma displays that were expected to grow quickly. PDPs were also considered high quality monochrome displays for industrial applications.

**Figure 3: Features and Uses of Various Flat Panel Displays**

| DISPLAY TYPE | LCD | LED | EL | VFD | PDP |
|---|---|---|---|---|---|
| | Non-light emitting elements | Slid light emitting elements | Solid light emitting elements | Vacuum discharge | Vacuum discharge |
| Sharpness | ☺ | 😐 | ☺ | ☹ | ☺ |
| Contrast | 😐 | 😐 | ☺ | 😐 | 😐 |
| Full color | ☺ | ☹ | ☹ | ☹ | ☺ |
| Half-tones | ☺ | ☹ | 😐 | ☹ | ☺ |
| Response | 😐 | ☺ | ☺ | ☺ | ☺ |
| Large screen | 😐 | ☹ | 😐 | 😐 | 😐 |
| Brightness | ☺ (backlighting) | ☺ | 😐 | 😐 | 😐 |
| Power consumption | ☺ | ☹ | 😐 | ☹ | 😐 |
| Cost | 😐 | ☺ | 😐 | ☺ | 😐 |
| Main applications | Calculators, word processors, PCs, TVs, vehicle displays | Outdoor signs | Word processors, PCs, vehicle displays | Car dashboards, audio equipment | Outdoor signs, TVs |

Source: Susumu Ohi, "Development of TFT-LCD and its application to notebook size PCs." Display Devices (Spring 94)☺, p. 25.

VFDs (vacuum fluorescent displays) were invented in Japan in 1967. After being applied to calculators, the market was expanded to consumer electronics like VCRs, audio products, home appliances such as microwave ovens and electric washing machines, car instrument panels, measuring instruments, office automation equipment and amusement equipment. As shown in Table 2, VCRs accounted for 28 percent of VFD uses, while electric home appliances accounted for 12 percent. A/V equipment represented another 28 percent, and vehicles provide 22 percent. The VFD is a triode that consists of an enclosed cathode, grid and anode in a high-vacuum tube. When the thermions are accelerated by positive voltage applied to grid and anode, they stimulate the fluorescent coating on the anode and light is emitted. VFDs are the brightest flat display, and is reliable and durable. VFDs provide dot-matrix displays (up to 256 x 128 dots) of excellent resolution at relatively low costs. They offer large character sizes up to 50 mm and tubes as long as 500 mm. This enables the display of sentences. Multiple tubes can be used on large information boards. Color dot-matrix VFDs offer attractive colors in amusement applications. Its weakness is due to its vacuum, which requires larger sizes to use thicker glass casings. Futaba Corporation is a leader in VFDs with up-to-date production, rapid development, and in-house production of parts and materials. The VFD business was 50 percent of Futaba's sales. While the technology was not considered mature, the $575 million market for VFDs in 1994 was expected to grow at only about one percent over the coming year.

**Table 2: Market Segments of VFDs (1993)**

| | | |
|---|---|---|
| Audio equipment | 25 billion yen | 34% |
| Image equipment | 23 billion yen | 32% |
| Car electronics | 8 billion yen | 11% |
| White goods | 7 billion yen | 9% |
| Business machines | 4 billion yen | 5% |
| Others | 7 billion yen | 9% |

Source: NEC Corporation.

Thin-film electroluminescent (EL) panel sales were expected to reach about $95 million in 1994 and $217 million by 1998. First discovered in 1937, thin-film EL panels using fluorescent materials deposited on a glass substrate were not developed until 1981. EL panels emit fluorescence when voltage is applied to elements containing zinc sulfide or other materials. EL displays can emit green, red or yellow light based on the use of filters, and new phosphor layering technologies to provide full color were under development. Advantages of EL over LCD and PDP displays included:

1. high resolution and large size (16-level gray scale, 1024 x 768 dots),
2. high contrast,
3. high refresh rates,
4. wide viewing angle,
5. lightweight, thin profile,
6. low power consumption.

EL devices with 12- to 14-inch screens, pixel pitch of 0.20 to 0.25mm, and display capacities of 1,024 x 768, 1,152 x 900, or 1,280 x 1,024 dots will become common displays for workstations. While expensive, these high contrast displays are used in space shuttle displays as well as vehicle navigation systems and office equipment, including laptop computers and word processors. Technical improvements of EL brightness and development of a full-color display would increase EL applications.

Light-emitting diode (LED) displays were first introduced in 1968 for use as discrete lamps, such as indicator lights for in-door electronic equipment, because of their low voltage, small size, light weight and long service life. LEDs emit light when current, passed through two types of semiconductors, converts electrons to light. Because of their excellent brightness, LEDs are often used on outdoor signs. The lower cost of VFDs and tungsten lamps for use as numeric displays forced LED makers to develop products with greater luminescence. In November 1993, a blue LED with high luminescence was developed, allowing the development of full-color LED displays. LED applications were now expected to grow rapidly. LEDs were used for fixed-pattern displays such as operating panels, alphanumeric clock displays and security company (stock brokers) trading boards, and public information boards at train stations and airports. The $380 million LED market was expected to reach $1.3 billion by 2000.

With sales of $4.2 billion in 1994, liquid crystal displays (LCDs) were the most popular flat panel display. In addition to being thin and lightweight, these displays could be run on voltages so low that they could be driven directly by an integrated circuit. Since they consumed so little power, they could run for long periods on batteries. They were free from flicker, and offered excellent legibility. LCDs were most adaptable to full color, were lower cost, and had good potential for further technological development. LCD applications expanded from watches and calculators to word processors, personal computers and other A/V products. With the development of small, energy efficient, light weight color TFT (thin film transistor) LCDs, the market for notebook computers had expanded, and new applications like personal digital assistants (PDA) and portable telephones were growing rapidly. While color LCDs and plasma displays penetrated the smaller screen CRT market, CRTs were still the best alternative for larger sized 20 to 40-inch displays.

LCDs were developed as display devices for watches and calculators. Applications spread to space-saving and personal use equipment, including LCD color TVs, LCD projectors, camcorders, and HDTVs. Applications in game machines and pinball games was also rising. Because of the thriving notebook and book-sized personal computer market, competition has intensified. Sharp Corporation, the world leader in LCDs, expected the market to reach $5.12 billion in 1994, a 22.7 percent increase over 1993. Japanese producers forecast LCD-type flat panel shipments to reach $10 billion by 1997, double expected 1994 shipments.

The Electronic Industry Association of Japan (EIAJ) estimated that the shipments of Japanese PCs totaled 1,441,000 units in the first half of 1993, of which 806,000 were domestic and 421,000 were for export. The introduction of extremely compact laptop and notebook computers created growing demand for thin, lightweight designs and low power consumption LCD panels. With color notebook computer models accounting for 60 percent of the total market, EIAJ estimated that the LCD market reached nearly $4.5 billion in 1993, compared with ETP's estimate of $3.9 billion. It is against this background that color LCDs, particularly TFT LCDs, were expected to continue their rapid growth in the future.

## Liquid Crystal Technology

The liquid crystal phenomenon was discovered by H. Reinitzer, an Australian, in 1888. Liquid crystal is an organic substance that has both solid crystalline and liquid characteristics within certain temperature ranges. Unlike liquid substances, liquid crystal demonstrated a crystalline structure and related refraction characteristics. Depending on the crystalline state, different refraction's are possible.

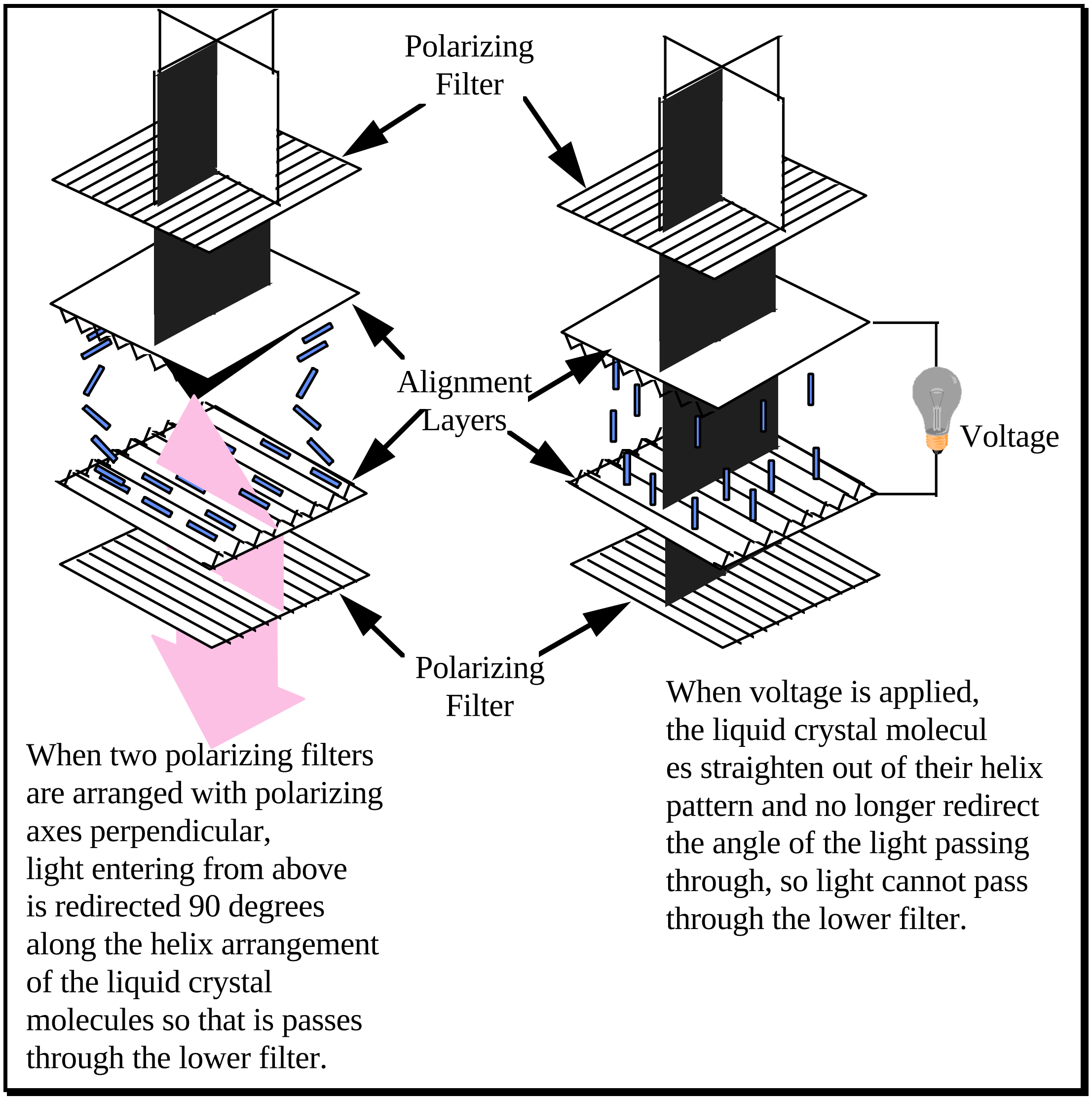
1. In the nematic phase, the long axes of the molecules lie in a largely parallel orientation when randomly distributed. When placed on a finely grooved surface, the molecules line up parallel within the grooves.
2. In the smectic phase, the parallel orientation of molecules are structured into layers.
3. In the cholesteric phase, the layers of parallel structures are stacked in a spiral structure. Reinitzer found this phase to act as a thermo-sensor.
4. In the discotic phase, a structure of plate-style molecules are combined like cylinders. This phase was discovered in 1977, but has yet to find an application.

In 1968, Williams of RCA Corporation discovered that the way light passes through liquid crystal changes when the liquid is charged with electricity. Five years later, Heilmeyer and his colleagues, also from RCA, applied this property in a display device. Calculators, digital watches, portable word processors, and notebook PCs all use nematic liquid crystals which change their structure with the application of electric voltage.

The LCD panel is formed by sandwiching liquid crystal between two super thin, grooved glass plates placed at 90 degree cross angles, or twisted, and attached to electrodes and polarized films. As shown in Figure 4, the twisted nematic (TN) technique is the basic method used for liquid crystal displays. The nematic liquid crystal properties are used to obtain two parallel orientations of molecules. The polarizing films that sandwich the liquid crystal are also crossed when the current is off, and the liquid crystal aligns its molecules in parallel with the polarized film. Thus the molecules are twisted at right angles (forming a 90 degree twisted helix) between the polarizing films. Incoming light twists at right angles through the molecules and penetrates the filter on the other side. If voltage is applied to the cell, the molecule's orientations are straightened and light can no longer penetrate the film as shown if Figure 4. In other words, when no voltage is applied, light passes; when voltage is applied, light is blocked and the area appears black. The voltage, therefore, triggers the liquid crystal to function like a shutter of a camera.

The development of this TN principle has evolved from simple elongated segments positioned to make numbers, to complex dot matrix segment systems used in character and graphic displays as shown in Figure 5. The elongated segment electrode is applied in calculators and digital watches for numeric applications. As shown, seven electrodes provide the basic structure for displaying any single number. Depending on the combination of electrodes that are activated, a number is displayed. Dot matrix techniques use a larger number of rows and columns to display the more complicated patterns of alphabets, symbols, and graphics. Color filters are placed over each display area, called a dot or pixel, in color displays. In dot matrix systems, red, green and blue filters cover each pixel so that a variety of colors can be displayed.

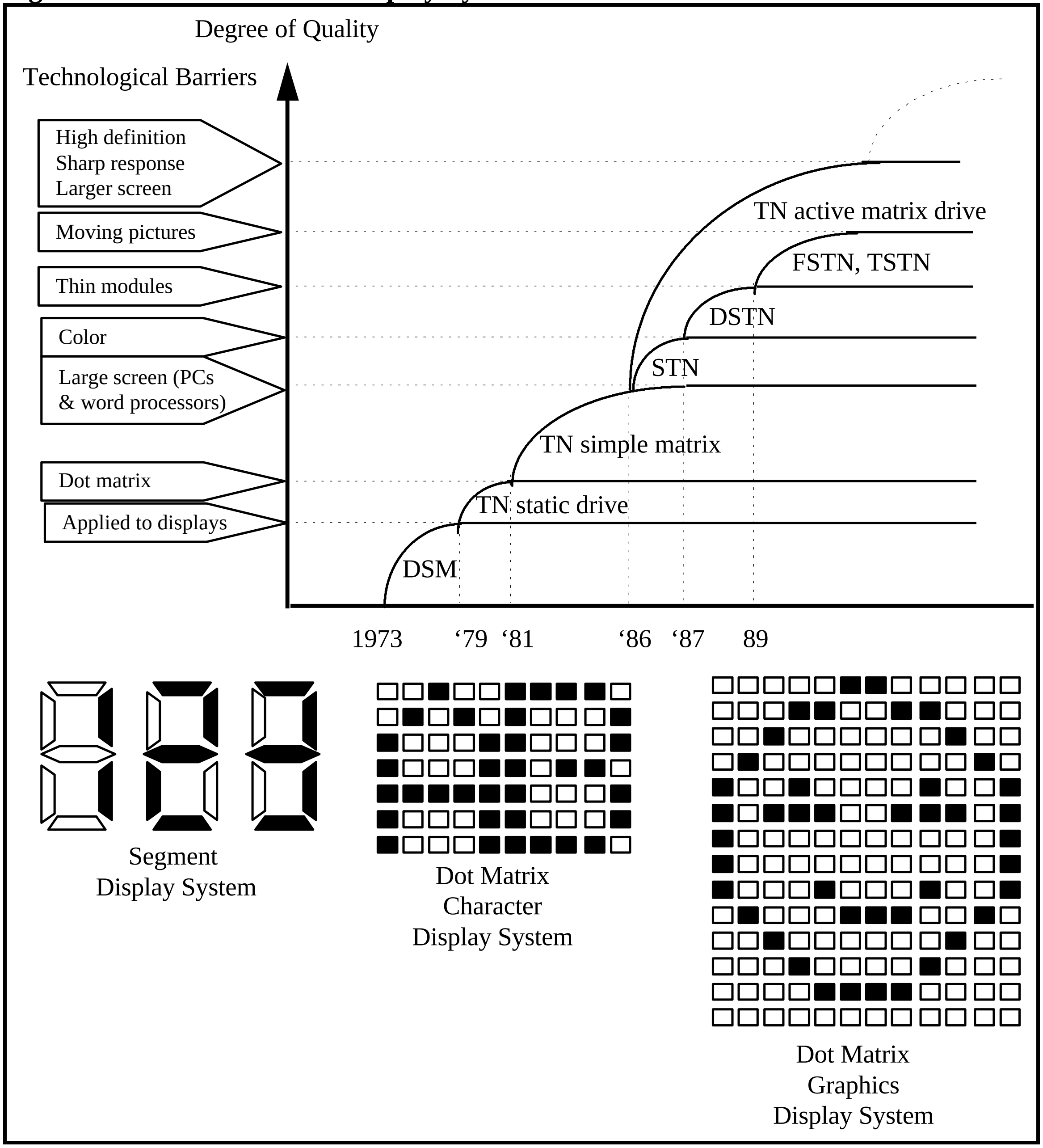
**Figure 4: Principle of Twisted Nematic (TN) Liquid Crystal Displays**




Source: “LCD Displays: The Leading Edge in Flat Panel Displays” (Sharp Corporation), p. 49.

The electrical or “drive” circuit used to activate liquid crystals is referred to as either simple-passive or active-matrix drives as shown in Figure 6. Passive-matrix drives are composed of vertical and horizontal belts of electrodes that intersect a pair of perpendicular electrodes called dots or pixels. When both axes of electrodes get voltage, the pixel shows an "on" status. Passive-matrix systems are used mostly in calculators, word processors, personal computers and other still image applications. Active-matrix techniques utilize separate switches for every pixel. This provides a better image contrast than the passive-matrix system. Active-matrix displays are used for TV and other moving picture applications which require high picture quality and fast response.

**Figure 5: Evolution of LCD Display Systems**

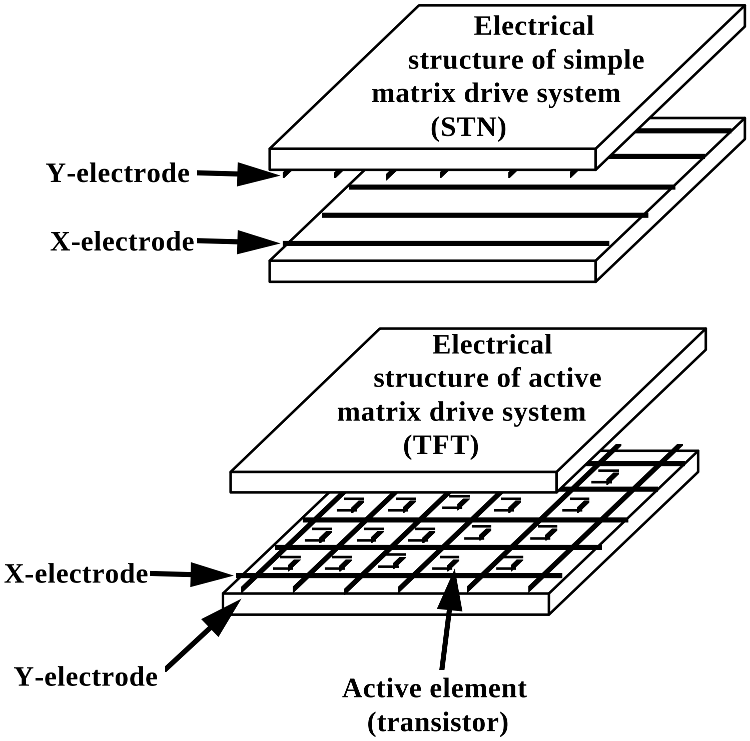



Source: "LCD Displays: The Leading Edge in Flat Panel Displays" (Sharp Corporation), pp. 50/90.

The application of alternative technologies results in three LCD types:

1. Super Twisted Nematic (STN) is a passive-matrix system that uses a twisted angle of 180 to 260 degrees. They can be colored yellow-green and blue. It is capable of making larger size LCDs than TN types which lose their contrast in large screens. As shown in Table 3, more advanced STN types include the double and triple super twisted nematic (DSTN and TSTN) types. These more advanced types provide for improved clarity and better color displays. DSTN uses two superimposed STN cells whose reversed twists cancel each others colored light and return to white. DSTN types are therefore thicker and

**Figure 6: Structure of Simple Passive and Active Matrix Drive Systems**




Source: Adapted from "LCD Displays" (Sharp Corporation), p. 61.

**Table 3: Simple Types of Twisted Nematic LCDs.**

| | TN | STN | DSTN | TSTN |
|---|---|---|---|---|
| Structure | Twists nematic crystals 90$^o$ | Twists nematic crystals 180-240$^o$ | Superimposes two STN cells (opposing twist directions) | Replaces DSTN compensation cell with plastic film |
| Color | Black/white | Yellow-green/dark blue | Black/white, multicolor | Black/white, multicolor |
| Features | • Low power consumption<br>• Thin, lightweight<br>• Low cost | • Large capacity display<br>• Thin, lightweight<br>• Lower power consumption<br>• High contrast | • Large capacity display<br>• Black/white display possible; applicable to color display | • Large capacity display<br>• Thin, lightweight<br>• Lower power consumption<br>• Color display |
| Problems or advantages | Cannot handle large capacity | Black/white display not possible (color display not possible) | Thin, lightweight, low power consumption | |
| Main applications | Calculators, watches, electronic organizers | Word processors (monocolor) | Word processors, laptop computers | Word processors, laptop computers |
| Main competitors | Easy to make, Citizen was a key maker in watches | Easy to make, OPTREX was strong in graphics | Sharp and Sanyo's passive color notebook applications | Word processor firms like Sharp, Toshiba, Casio, Hitachi, Sanyo , Hoshiden, and Citizen |

Source: Adapted from LCD Displays (Sharp Corporations), p. 65.

heavier than STN types. TSTN uses a compensating polymer film above and below the operating cell to give improved color. FSTN (film super twisted nematic) uses only a single-layer of this compensating polymer film.

2. Active-matrix Thin-Film Transistor Twisted Nematic (TFT-TN) types have three electrodes to act as transistor switches located at every pixel. Its production cost is much higher than passive matrix, but it provides a much sharper image that is more suitable for color displays. Sharp introduced a 21-cinch multicolor display in 1994. In late 1993, Nikkei Microdevices reported that multi-color, 10-inch TFT displays cost $1500 compared to $750 for the same size of STN graphics color display. It was estimated that the price of the TFT display would fall to about $600 by the end of 1995. Sharp Corp. estimated that the price would fall to $500 by 1996. A full-color (16.7 million colors), 4-inch TFT LCD display for TVs cost about $180. It's price was expected to fall to $120 by the end of 1995. Sharp introduced the largest (8.4-inch) full-color display for $5,000 in 1994 and was attempting to develop a 10.4" full-color display as a potential CRT replacement display.
3. Metal-Insulated-Metal Twisted Nematic (MIM-TN) is essentially the same as TFT-TN, except that it uses a single thin-film diode as its switching device. The quality is lower since it is slower than the TFT-TN type, but it is cheaper to manufacture. Seiko Epson was a leader, producing three million units per year for Pachinko machines (Japanese pinball games). While it did not provide high quality images, it was inexpensive and easy to replace when broken. It was expected to be in trouble if 10.4-inch TFT LCD prices fell to $600.

Table 4 provides quality and cost comparisons of STN, TFT, and MIM displays. The total market size for 1993 was split 55-45 between STN (65% black and white and 35% simple color) and TFT sales. Sharp's LCD forecast for 1994 was $5.4 billion, split 45-55 between STN (40% black and white and 60% simple color) and TFT sales. By 1996, Sharp expected the market to reach a $10 billion, split 30-70 between STN (40% black and white and 60% simple color) and TFT sales.

Table 5 shows the features of different active and passive drive systems and the alternative LCD systems. As can be seen from the table, an active matrix system using the TN type of LCD with a TFT driver offers the best overall performance. This TFT-TN display integrates traditional nematic liquid crystal and microscopically small, thin film transistors. The transistor switches are located on each individual picture pixel and have a function of improving deficiencies in twisted nematic. TN cannot store the picture data without continuos electric voltage to keep the image on the display. This voltage is supplied by the transistors.

TFT-TN is expensive and difficult to produce in larger sizes. The thin-film transistor panel -- basically a giant semiconductor -- consisted of transistors implanted beneath each pixel; one faulty transistor and the entire display had to be scrapped. Display screens for standard personal computers comprised about 300,000 pixels. Modern television sets had 600,000 pixels. High resolution systems, like those used for CAD workstations, required as many as 10 million or more pixels. With market demand growing for more and larger LCDs, the number of pixels would increase, making the production problem even more serious.

**Table 4: LCD Technology Comparisons**

| **Type of LCD** | **STN**<br>**Passive** | **TFT**<br>**Active** | **MIM**<br>**Active** |
|---|---|---|---|
| **Structure:** | X and Y electrodes laid out in a vertical and horizontal lattice | A silicon thin film semiconductor which performs switching is sandwiched between the X and Y and opposing electrodes | An insulator which performs switching is sandwiched between the X and Y terminals. |
| **Features:** | Simple production and low cost | High contrast and picture quality; superior response, and halftone display possible | Cost and picture quality are between STN and TFT |
| **Problems:** | Picture quality drops with increased size, halftone response poor. | High cost | Neither lowest cost or highest quality |
| **Quality:** | | | |
| display contrast | 20:1 | 150:1 | 100:1 |
| viewable angle | 60 | 120 | 100 |
| response speed (ms) | 300 | 50 | 50 |
| brightness (candela/m2) | 60 | 60 | 80 |
| flickering | strong | weak | weak |
| voltage leaks (crosstalk) | high | almost none | little |
| **Cost:** (yen) | | | |
| glass cutting | 2,000 | 25,000 | 2,000 |
| color filter and assembly | 8,000 | 8,000 | 10,000 |
| yield percentage | 50% | 50% | 50% |
| module cost | 28,000 | 30,000 | 35,000 |
| total cost | 48,000 | 96,000 | 79,000 |
| **Applications:** | Primarily still images such as the electronic organizer, word processors, and personal computers. | TVs, projection displays and other moving picture applications | Word processors, personal computers, TVs. |
| **Competitors:** | Sharp held a 36% market share in 1993 | Sharp held a 53% market share in 1993 | Seiko-Epson was the largest maker. |

Source: "Flatpanel Display 1992," Nikkei Business Publications, p. 73.

Thin-film transistor liquid crystal displays (TFT-LCDs) are the most suitable for use in notebook computers. They are thinner and lighter than CRT displays. Sharp produced a 9.5-inch TFT-LCD for PC notebooks that was 10 mm thick and weighed 590 grams in 1994, one-half its 1990 thickness and one-third of its previous weight. The thinnest 9.5-inch TFT-LCD, made by Mitsubishi, was 8.9 mm thick and weighed 550 grams. It incorporated a 3 mm diameter cold cathode ray tube for backlighting and was assembled using tape automated bonding technology[5] for assembly. Sharp offered a 6.4-

[5] Tape automated bonding is higher cost in that circuits are preassembled on plastic tape for high precision assemply.

inch TFT-LCD that was only 6.8 mm thick, the thinnest screen ever made for color information terminals.

**Table 5: Comparison of Various Types of LCDs**

| DRIVE SYSTEM | LCD TYPE | DISPLAY PERFORMANCE | | | | | RESPONSE (MOVING PICTURE APPLICATIONS) | LARGE SCREEN | COST |
|---|---|---|---|---|---|---|---|---|---|
| | | DISPLAY CAPACITY | CONTR AST | FULL COLOR | HALF TONES | VIEWING ANGLE | | | |
| Duty ((Passive) Drive | TN | ☹ | ☹ | 😐 | ☹ | ☹ | 😐 | ☹ | ☺ |
| | STN | 😐 | ☺ | ☹ | 😐 | 😐 | 😐 | ☺ | 😐 |
| | DSTN | 😐 | ☺ | ☺ | 😐 | 😐 | 😐 | ☺ | 😐 |
| | TSTN | 😐 | ☺ | ☺ | 😐 | 😐 | 😐 | ☺ | 😐 |
| Active Matrix Drive | TN-TFT | ☺ | ☺ | ☺ | ☺ | ☺ | ☺ | 😐 | ☹ |
| | TN-MIM | 😐 | ☺ | ☺ | 😐 | ☺ | 😐 | 😐 | 😐 |

**Source: "LCD Displays: The leading edge in Flat Panel Displays" (Sharp Corporation) p. 65.**

There was a number of technology improvements underway for LCD panels as shown in Figure 7. Sharp Corp. outlined a number of developments:

- *Enlarged display sizes.* In June, 1994, Sharp developed a 21-inch, 16,700,000-color TFT-LCD. A 40-inches screen was considered possible.
- *High-definition imaging.* Sharp developed a 17-inch XGA (1,024 x RGB x 768 dots) TFT color LCD for engineering workstations. The company also developed 2-inch polysilicon TFT-LCD panels for high definition projection in October, 1993. As shown in Figure 8, TFT-LCD developments were expected to continue to move towards high resolution displays.
- *Wide angle vision.* Sharp announced a 14-inch TFT color LCD in September, 1993, with an angle of vision expanded vertically to 80 degrees, more than double compared with previous panels.
- *Lower power consumption.* Sharp announced a 5-inch reflection type TFT color LCD with no back light for use in portable information processing equipment that used less than 50 mW of power. Development of 2 W 8.4-inch and 3 W 10.4-inch LCD units was underway.
- *Thinness and lightness.* Sharp developed a 9.6-inch LCD unit with 8mm thickness and 350 g weight. Reflection type displays could be as thin as 2mm. Prototypes using plastic wafers were one-half the weight and one-third the thickness.
- *Cost reduction.* Sharp's goal was to sell 10-inch VGA TFT color LCDs for $500 by 1996. This required technical breakthroughs in process materials, color filters, driver LSIs, peripheral circuit components, manufacturing systems, and inspection and correction methods.[6]

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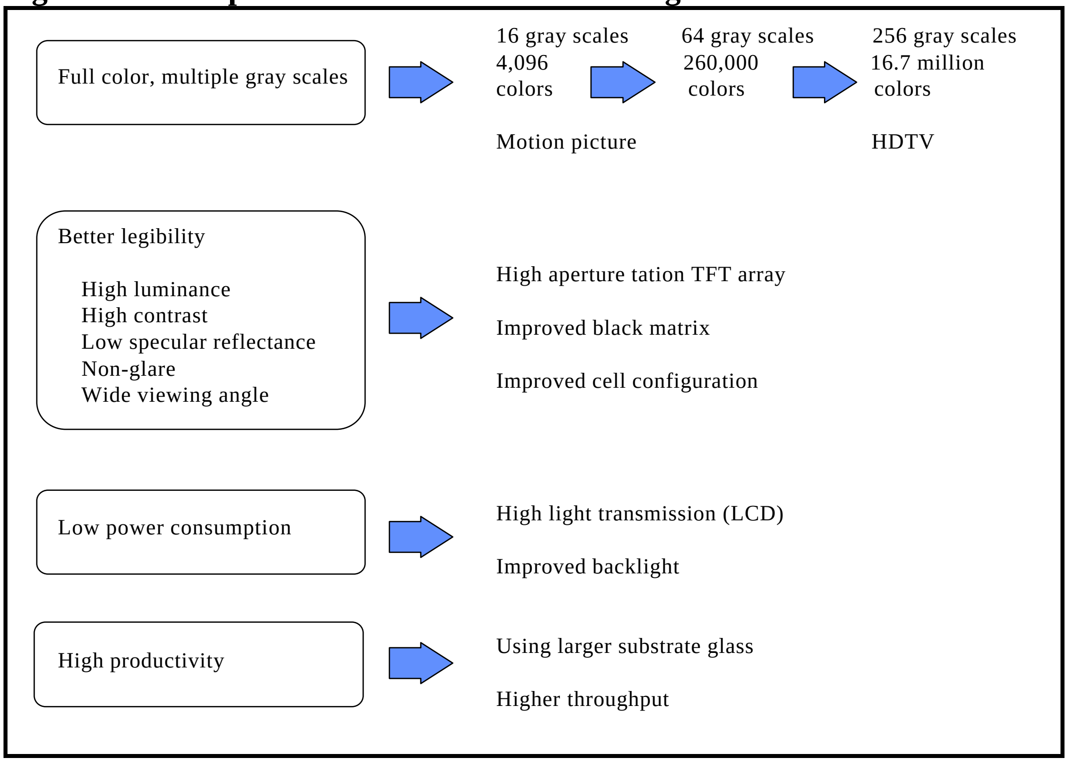
[6] Ohshita, Shinji, "Liquid crystal display (LCD) and future appplied products, Science and Technology in Japan. September 1994, pp. 43-46.

**Figure 7: Development Efforts for LCD technologies**



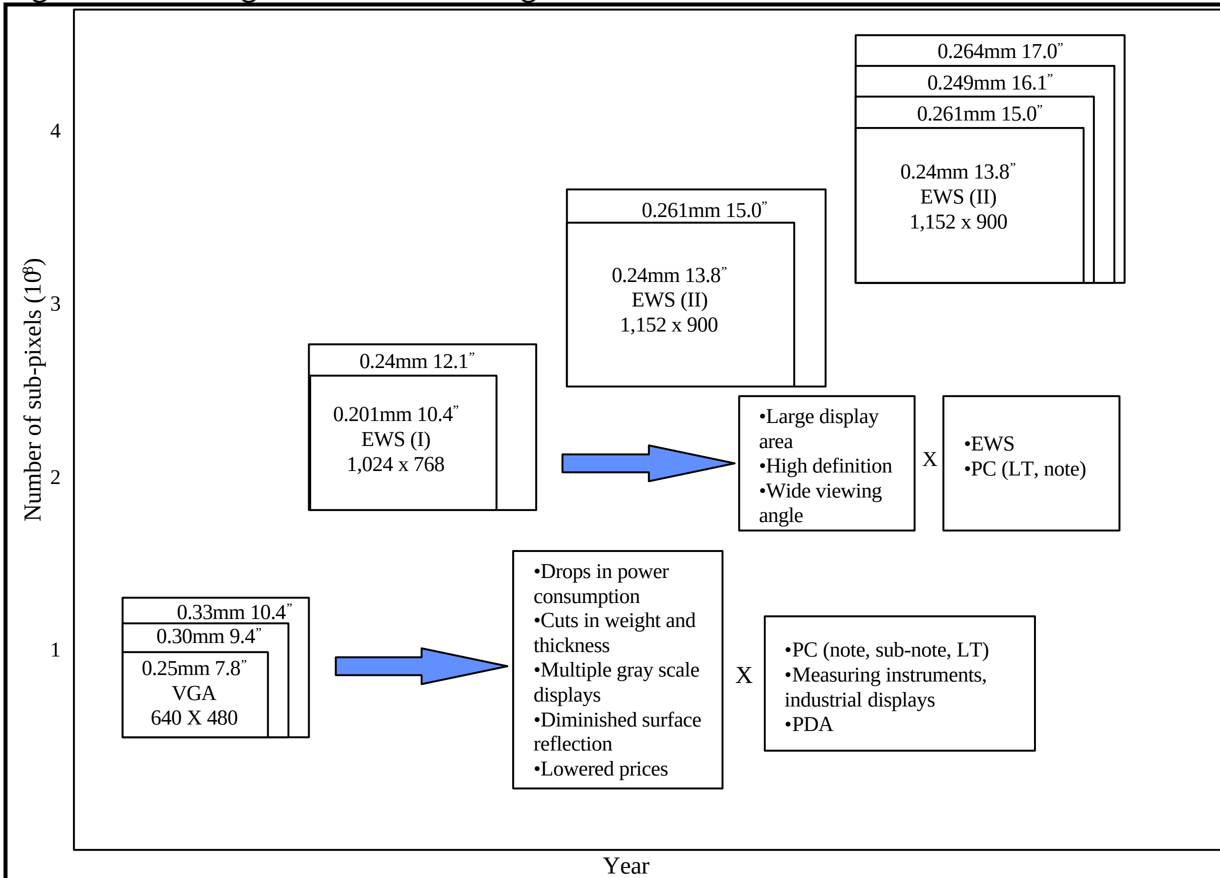

Source: Sakai Arai, “Developers Cultivate TFT LCDs Specifically for Notebook Computers,” *Display Devices*, Spring ‘94, p. 14.

Requirements for TFT-LCDs by the year 2000 were expected to increase as shown in Table 6. High definition applications would push the resolution and size demands. Office equipment would push the pixel size. Mobile units would push the brightness, thickness and power consumption requirements. Increasing TFT-LCD brightness was a challenge. Light emitting tubes of 300 candela/square meter becomes only 100 candela/square meter in TFT-LCD applications. The major portion of light received by the screen was absorbed or blocked by the TFT-LCD filters and circuitry. Metal parts of TFT devices, or the color filter, or board polarization reduced the original light source to a small percentage of the original source. To improve brightness, the TFT “opening rate” (the percentage area of a pixel that allows light to pass) had to be improved. Miniaturization and micro fabrication technologies did not help the problem if pixel size was also reduced to meet higher resolution requirements. If more light was added, more power was needed, thereby defeating the low power advantage of the LCD system.

To cut costs, Sanyo had also developed a quasi-full color IC for its TFT-LCD system. The 8-bit signal that displays 260,000 colors are expressed with 3 bit ICs that cover 4,000 colors. This mechanism allows pricing at $300, cheaper than comparable full-color formats. A TFT film technology utilizing a three layer masking technique that Sanyo introduced is also expected to contribute to making larger screens at lower prices. LCD panels could be connected together to make larger screens. Fujitsu had prototyped a four-panel, 24-inch screen. Sharp had also prototyped a 4-panel, 21-inch screen. Naotake Orihara, technology manager for Fujitsu's LCD division, noted:

> This method should allow commercial production of panels as large as 200 inches in the future. For those trying to enlarge single panels as much as possible, this reversed line of thinking is a big surprise.

**Figure 8: Evolving Trend Towards High Resolution LCDs**




Source: Arai, Sakai (1994), "Developers Cultivate TFT LCDs Specifically for Notebook Computers." Display Devices Spring '94, p.14.

**Table 6: TFT LCD Requirements by 2000.**

| | Office Equipment | Hi-Definition | Mobile/Automobiles |
|---|---|---|---|
| Size | 17-inch | 30-inch | 6-inch |
| Pixels | 1280 X 1024 | 1920 X 1035 | 320 X 240 |
| Pitch | 0.27mm | 0.345 X 0.36mm | 0.375mm |
| Color | Full-color | Full-color | Full-color |
| Contrast | 100:1 | 100:1 | 100:1 |
| Angle | 90° | 90° | 90° |
| Response time | 30 mili-seconds | 20 mili-seconds | 20 mili-seconds |
| Brightness | 150 candela | 200 candela | 300 candela |
| Thickness | 10 mm | 25 mm | 6 mm |
| Weight | 1kg | 7kg | -- |
| Power consumption | 15 watts | 50 watts | 3 watts |

Source: Nikkei Sangyo November 22, 1993, p. 9.

A nine-panel screen would become a 40-inch diagonal display.

Increased size has also been accomplished with projection systems. While applications over 30 inches in size could go to plasma display technology, it was difficult to displace low cost CRTs for such applications. For 10-inch PC screens, TFT-LCDs were nearing equal value-added to CRTs. TFT-LCDs were perfected for that applications. If LCDs costs fell to $250, CRTs would be in serious trouble. According to Nikkei Sangyo newspaper, of the $4.3 billion market in 1993, $2.5 billion was accounted for by notebook PCs and workstations. PC and workstation applications were forecast to continue dominating LCD sales with $3.5 billion in 1994, and $5.5 billion by 1996. Portable information tools (PDAs) like the Apple *Newton* and Sharp *Zaurus* were projected to be one of the fastest growing markets, accounting for nearly $1.5 billion in LCD sales by 1996. Amusement applications (games) were expected to stay steady at about $500 million. HDTV applications were forecast to triple in size to about $900 million by 1996. Car navigation systems, also a new product, were expected to reach $500 million in sales by 1996. Other applications would account for about $1.7 billion in LCD sales by 1996.

Sanyo was competing with STN-LCDs which did not handle moving images or provide the same level of contrast as TFT products. To overcome the problem, Sanyo was attempting to reduce cell thickness to 2 microns. Successful developments in STN technology could possibly reverse the position of STN and TFT applications in the future.

**Alternative Technologies**

Texas Instrument, Inc. (TI) had been developing a new digital micromirror display (DMD) technology. The system is based on semiconductor technology so costs can be reduced through mass production. DMD uses SRAM (static random access memory) with aluminum mirrors to convert images into digital signals that are stored in memory. Each memory continuously reflects red, blue and green color signals. By tilting the mirror, the signals switch on and off to form images. A 37mm x 32mm chip has about 2 million mirrors. It features 256 gray scales with 8 bits for each color, or a total of 26 bits to support color display. In 1992, TI demonstrated a projection display with 640 x 480 pixels using this technology. At the 1994 Society of Information Display (SID) show, TI unveiled a prototype system with 1,920 x 1,035 pixels, a substantial improvement in brightness, response time, contrast ratio and resolution from the previous model. TI’s portable projector, weighing 6.8kg., provides a screen size of over 40 inches and meets all TV set requirements, from U.S. NTSC to European PAL systems.

Kent Display Systems introduced a new LCD technology as displays for such applications as traffic signals, telephone and pager displays, POS terminals, outdoor billboards and information terminal equipment. The polymer stabilized cholesteric structure (PSCT) LCD technology, developed at Kent State University, enabled the first low power consumption display without the need for backlighting. Its brightness and contrast ratio allows users to read characters outdoors under sunlight, offers high-resolution, and reduces cost. The new venture has about 20 employees.

One alternative to TFT-TN technology is called ferroelectric liquid crystal (FLC) which was first used in 1975. These liquid crystal molecules are endowed with a positive or negative polarity in their natural state, even without the application of an electric field. In other words, FLCs utilize intrinsic polarization and will hold the last arrangement of molecules when voltage is removed, retaining their image intact without voltage. FLC applies a passive matrix structure that is far less complicated and cheaper to produce. For example, an FLC display with 1000 by 1000 pixels needs only 2000 electrodes, compared to 1,000,000 TFTs. FLC also allows for rapid switching, over 3,000 times faster than TN LCD displays, vivid pictures from any viewing angle or at any size, and data storage allowing for high quality, high resolution applications. The costly TFT transistor is replaced by the material itself, thereby reducing the cost of production.

FLC technology, previously referred to as the illusionary LCD, had several technical hurdles to overcome before becoming commercially applicable. The most significant problem is the quality of alignment of the smectic phase, on which the technology is based. It is more sensitive to mechanical stress than the nematic phase used for TFT displays. Development of practical ferroelectric LC mixtures was considered key for its technical success. But Canon Corporation introduced prototypes of two 15-inch FLC monochrome and color stand-alone PC monitors at the LCD International exhibition in September, 1994. The color display offered 1280 x 1024 pixels. The monochrome model offered 2560 x 2048 pixels. These displays, however, were not capable of full-color TV applications. These monitors were reported to be difficult to produce in volume. It was expected to be cheaper and better for larger sized screens, but did not have the full color used for moving pictures. If FLC technology is successful, it could quickly displace TFT as the lower cost, high quality display for most CRT applications.

Other American makers had focused attention on field emission displays (FEDs). SI Diamond Technology of the U.S. introduced a 1-inch active diode FED with 125 x 125 pixels using laser-processed diamond thin-film. Amoco Corp. and Zenith Electronics Corp. followed up with a report concerning the structure and material of FEDs and their application to large-sized screens. These were not yet ready for significant applications.

## Primary LCD Markets

The growth in multimedia (i.e. the integration of text data, graphics, video images, and/or audio signals) required improved information processing and displaying technologies. Multimedia would increasingly utilize telephone circuits, satellite broadcasting, CD-ROM, and CATV. It also required recording, editing, transmission and retrieval of information. LCDs had become an indispensable device in providing the human interface for information related technologies. While there were wide discrepancies between forecasts for the growth in these technologies, it was expected to have a significant impact on society. Some of the primary markets included:

- Notebook type PCs and workstation had an estimated LCD demand of $3.3 billion in 1994 with projected growth to $5.5 billion in 1996. The shift to color displays in the field of notebook type PCs is proceeding at a faster pace than initially estimated. Color LCDs had grown in market share from 49.1% in 1992, to 69.5% in 1993, to an estimated 87.3% in 1994. STN color LCD was expected to become the main display for multi-color notebook type Pcs used for graphics and document processing. TFT color LCDs had advantages in larger, full color, thinner, lighter, and lower power displays.

- Portable information processing terminals had an estimated LCD demand of $130 million in 1994 with projected growth to $135 million in 1996. Lightweight, compact, low power systems would see a shift from STN LCDs to reflection type DSTN-LCD and plastic LCD panels. TFT-LCDs for color were also expected to have a market.
- High-definition audio-video systems had an estimated LCD demand of $340 million in 1994 was projected to reach $790 million in 1996. The growth of camera-player systems would spread to TV telephones, interactive multimedia terminals, and hi-definition wall type TVs. Large screen and projection type LCD systems provide portability and hi-definition video information display systems usable with computers.
- Vehicle-mounted navigation systems had an estimated LCD demand of $83 million in 1994 and projected to reach $500 million in 1996. The navigation/TV system would be the main type in Japan, with low-cost navigation only being used in the U.S. Combination systems will use TFT-LCDs. Navigation only systems will use STN-LCDs.
- Amusement applications had an estimated LCD demand is $440 million in 1994 with growth projected to $540 million by 1995. High performance amusement equipment graphic functions, using 32Mb CD-ROM chips, were expected to drive next generation game systems.

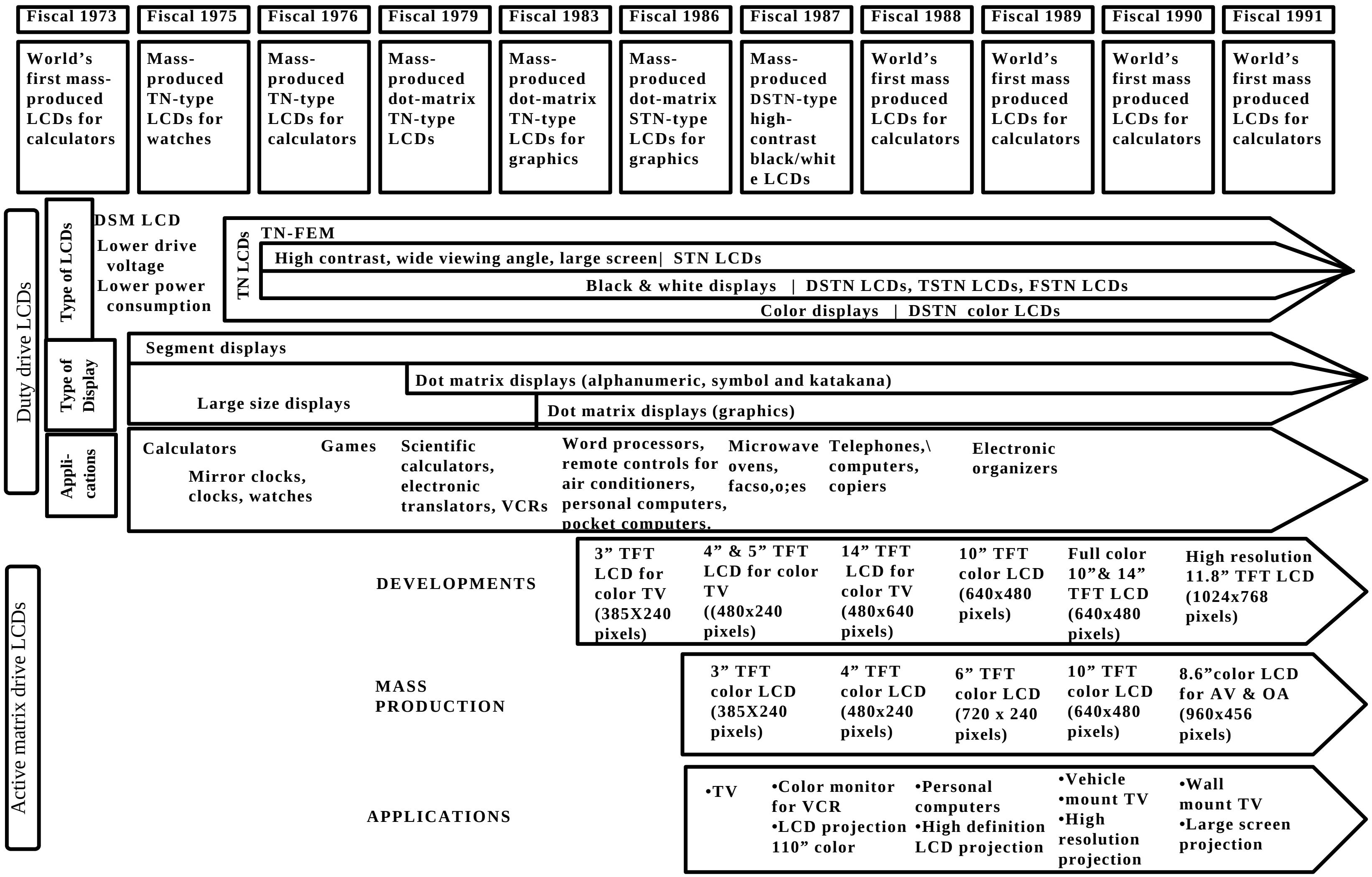
As shown in Figure 9, the development and marketing of LCD products continues to evolve. The continued introduction of technological breakthroughs has allowed for new applications that have spurred LCD market growth.

## Major LCD Competitors

Japanese makers are developing high-precision, high-resolution color LCDs with low power consumption at a low price designed for notebook computers, car navigation systems, workstations and other applications. Offered at reduced prices as a result of mass production, LCD and other flat panel displays have fueled rapid growth in the personal computer market. The major players in the LCD market were Japanese firms as shown in Table 7. Newspaper estimates were often disputed by Sharp representatives. Sharp dominated sales with 45 percent of the LCD market and supplied about 70 percent of its sales to other manufacturers. Sharp estimated the total LCD market for 1993 at $4.29 billion, rather than the newspapers $5.8 billion.

Sharp's LCD sales were reported at $1,875 million in 1993, and estimated to end 1994 at $2,450 million. Sharp shipped 2.3 million units in 1993. Sharp had an estimated 55% of the TFT market with 1.6 million units sold. By the second half of 1994, most production capacities exceeded those reported in 1993 (Table 8). Sharp was producing 240,000 large TFT-LCD panels per month by late 1994, 80,000 passive (monochrome and color) LCD panels per month, and 120,000 EL units per month. Production sites were in Nara and Tenri Japan. Investment was planned at 80 billion yen between 1993 and 1995, to primarily increase TFT production. With the opening of the world's largest flat panel display factory in Mie Prefecture in July, 1995, Sharp would have additional capacity of 150,000 large color TFT LCD panels per month. The 53 billion yen first phase of the Mie

## Figure 9: Development and Marketing History of Sharp LCD Products




Source: "LCD Displays: The Leading Edge in Flat Panel Displays" (Sharp Corporation), pp. 66-7.

**Table 7: LCD Panel Sales Reported by Manufacturers**

| ($ millions) | FY 1992 | FY 1993 | FY 1994 |
|---|---|---|---|
| Sharp | 1360 | 1800 | 2300 |
| Seiko-Epson | 700 | 700 | 750 |
| Toshiba | 400 | 550 | 1000 |
| NEC | 160 | 420 | 900 |
| Casio | 350 | 400 | 600 |
| Optrex | 360 | 400 | 440 |
| Hitachi | 250 | 300 | 360 |
| Sanyo | 320 | 300 | 420 |
| Hoshiden | 195 | 270 | 400 |
| Matsushita | 200 | 260 | 390 |
| Citizen | 250 | 250 | 300 |
| Stanley | 115 | 150 | 160 |
| Total | 4660 | 5800 | 8020 |

Source: Nikkei Sangyo Newspaper, 4/6/94

**Table 8: Production capacity of large size color LCDs (10-inch equivalents)**

| Competitors | TFT sheets/month | STN sheets/month | Planned capacity |
|---|---|---|---|
| Sharp | 45,000 | 45,000 | 90,000 TFT, 90,000 STN |
| NEC | 20,000 | - | 84,000 TFT |
| Toshiba | 20,000 | 10,000 | 30,000 TFT, 25,000 STN |
| Seiko-Epson | - | 5,000 | 10,000 STN |
| Hitachi | 5,000 | - | - |
| Sanyo | - | 15,000 | - |
| Kyocera | - | 1,000 | - |

Source: Yano Report, June 10, 1993.

site was to open the first half of one building in a location that had space for four buildings.

As shown in Tables 9 and 10, NEC and Display Tech. Inc. (DTI, a Toshiba/IBM joint venture) were working to gain position in the rapidly growing market. DTI was investing 40 billion yen in expanded facilities to open by late 1995. Toshiba was producing a full range of displays. Small and medium sized TFT and STN displays were produced in Himeji; TFT and STN in Fukaya, and large sized TFT for PC and workstation applications were being produced at DTI. Toshiba's 100,000 unit monthly production at its Himeji plant was to produce 80 percent color LCDs by the end of FY 1994. IBM had also begun to produce LCDs on its own, and Toshiba was planning to produce 400,000 large panel TFT-LCDs per month by 1995. At this rate, Toshiba's capacity was projected to equal Sharp's TFT-LCD capacity by the end of 1995.

NEC had been an early entrant in TFT panel production and produced its first notebook computer using TFT color LCD panels in 1991. NEC specialized in TFT for PCs, and planned to produce small and medium sizes for car TVs and navigation systems.

In-house consumption accounted for 90 percent of NEC's output. NEC Kagoshima was NEC's main production base with its second phase production line having begun operation in December, 1992. The first phase produced two 10-inch panel from a single glass plate. The second-phase production line produced four panels from a single glass plate. NEC's vice president of display devices, Haruki Horikiri, explained:

> The throughput doubles by producing more panels from a single glass plate and yield increases 20 to 50 percent. With these improvements, productivity increases from the first-phase lines. However, productivity of third-phase production lines installed after 1996 must be five or six times greater than that of the first-phase lines. Many LCD makers are planning for the third phase lines. One way is to enlarge the size of glass plates so that a single glass plate renders more than four plates. However, if a substrate glass plate results in a deteriorated yield, it defeats the original purpose.

**Table 9: Trends in Production Capacities of Key LCD Makers***

| Leaders | FY 1993 | FY 1994 | FY 1995 | FY 1996 |
|---|---|---|---|---|
| Sharp | 1,000 | 1,300 | 2,100 | 3,100 |
| NEC | 600 | 1,200 | 2,000 | 2,500 |
| DTI | 600 | 1,000 | 1,800 | 2,400 |
| Others | 100 | 500 | 1,000 | 2,000 |
| Total | 2,300 | 4,000 | 6,900 | 10,000 |

*(000) units of 9.4-inch equivalent annual production capacity.
Source: NEC Corporation

**Table 10: Investment for Production by Major LCD Manufacturers (billions of yen)**

<table>
<tr><th></th><th>1990</th><th>1991</th><th>1992</th><th>1993</th><th>1994</th><th>1995</th></tr>
<tr><td>Sharp</td><td>3.2</td><td>3.5</td><td>4.0</td><td colspan="3">8.0</td></tr>
<tr><td>Toshiba</td><td>2.5</td><td>1.5</td><td>2.0</td><td colspan="3">8.0</td></tr>
<tr><td>NEC</td><td>1.0</td><td>2.0</td><td>1.2</td><td>2.0</td><td></td><td></td></tr>
<tr><td>Hoshiden</td><td colspan="2">2.0</td><td>4.0</td><td colspan="3">2.0</td></tr>
<tr><td>Casio</td><td>.6</td><td>1.3</td><td colspan="2">3.8</td><td></td><td></td></tr>
<tr><td>Fujitsu</td><td colspan="2">1.0</td><td colspan="4">2.7</td></tr>
<tr><td>Canon</td><td></td><td></td><td colspan="3">1.5</td><td></td></tr>
</table>

Source: Yano Report, June 10, 1993.

NEC's second phase had a capacity of 160,000 panels. Production of 50,000 TFT panels per month was added at NEC Akita in December, 1994, with planned expansion to 100,000 units. According to Horikiri:

> Since we stared our LCD business, we have tried to reach an annual sales target of $1.0 billion by 1996. However, a surge in demand has led us to believe we can reach our goal this year. We will continue our efforts to maintain high-yield production and expand our line of products.
>
> One of the superior features of our full-color TFT-LCD panel is our excellent driver IC technology. The LCD panel is a product that can replace CRTs because it can display images. Therefore, the same picture display quality as CRTs is necessary. If a maker relies on the lightweight and low power consumption of LCD panels, compromising picture quality, it would eliminate half of TFT-LCDs' key features.[7]

[7] "NEC Expands to Meet Demand for TFT LCDs," *Display Devices '94*, Spring 1994, pp. 8-13.

NEC had invested $200 million for phase one, $250 million for phase two at Kagoshima, and $300 million for the Akita line. The cost included construction of ancillary equipment, including a clean room.

Tottori Sanyo Electric Co., Ltd. was also committed to the electronic display devices industry. In the past three years, the company had invested $250 million in production lines for STN color LCDs. The company was a leader in super-twisted nematic (STN) LCD mass production and was working to make their picture quality competitive with TFT-LCDs. According to Noriaki Nishina, general manager of Sanyo's LCD division:

> The LCD industry in Japan has focused almost exclusively on TFT models. In contrast, Tottori Sanyo Electric has concentrated on STN-LCDs. Being one of the few suppliers of these products is advantageous for our company.

Global sales of LCDs had doubled in 1994. With its lower price tag, STN-LCDs had become a key color display for PCs. Sanyo was doubling its monthly output of STN color LCDs to 180,000 units of 10-inch panel equivalents by April of 1995. Over 90 percent of the company's output was in color displays. According to Nishina:

> We have a 3:1 ratio of production facilities for STN products and for TFT products. Right now, we cannot satisfy user demand with our output of TFT-format products. By next spring, though, we will have expanded our production of TFT-format products from the 60,000 units we make now to 130,000 units a month.

Development goals included wider viewing angles and larger screen sizes. Nishina continued:

> We will cultivate the necessary levels of technology and skill in these products, while lowering production costs and providing the advanced performance that users demand.[8]

To address the shortage of color filters for TFT-LCDs, the company began producing color filters in August, 1994. Until now, color filters had been produced by chemical and printing companies.

Others, like Hoshiden, had invested $300-400 million in LCD expansion by 1994 and were also planning to add TFT-LCD capacity by the end of 1995. According to Hoshiden's vice president, Shigeo Aoki, its second plant would begin construction by the end of 1994:

> We want to respond to expanding demand for displays for PC notebook computers. We plan to set up 100,000 units (large 10-inch size equivalents) per month capacity in the first stage of our construction plan. We will triple that capacity over the future.

By the completion of its $600 million expansion, Hoshiden would be one of the largest producers in Japan. With only $860 million in sales, the company had issued $110 million of convertible debenture bonds in Switzerland in July, 1994, to finance its expansion.

Seiko Epson produced monochrome STN and TN in its Toyoshima factory, but was expanding into MIM and TFT in its Suwa facilities. Small TFTs were supplied for viewfinders. Hitachi was also one of the first to mass produce 10-inch color LCDs in Japan. The company had also developed thin, passive-matrix LCDs with high

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[8] "Tottori Sanyo's Efforts with STN LCDs Lead to Demand Gains, Output Growth," *Display Devices '94*, Fall 1994. Pp. 34-35.

performance, using film super-twisted nematic (FSTN) technology. Hitachi had just invested $300 million to expand facilities in its Mobara City operations.

NEC's Horikiri felt that Japanese firms leadership in TFT-TN display technology would continue. He explained:

> Now, Japanese companies account for 95 percent of the world's LCD production, staying well ahead of foreign manufacturers. A company that wants to enter the TFT LCD business must make equipment investments and have the same technical capacity as a memory chip business. For this reason, it is very difficult for businesses in the United States and Europe to enter into the TFT-LCD business.
>
> In South Korea, Samsung has already installed test-manufacturing lines with strong financial backing. Also, a consortium of enterprises formed in the United States to manufacture flat panel displays. IBM has already started expanding into this business on its own. With all of this in mind, we have to consider relations among competitors.
>
> Japanese makers are trying to shift comprehensive production overseas. I wonder if comprehensive production of LCDs is possible considering procurement of materials and preparation of infrastructures. For the Japanese semiconductor industry, the high yen value will make it necessary to shift production of LCDs overseas in the near future. There is also a need to establish maintenance systems overseas and to design panels in response to local users' needs. Since the United States lifted its anti-dumping measures, Japanese personal computer makers are beginning to assemble notebook computers there. As a result, there is a growing need to produce LCD panels in regions near the end users.[9]

**The Threat from Overseas Competition**

Unlike semiconductors, LCD makers could not expect to earn high margins with the introduction of each new generation LCD display. For example, NEC's LCD technology development manager, Mitsutaka Morimoto, says that the current pixel pitch (size) of 200 microns already reaches the limit of human vision capability and needs no further reduction. With no replacement technology seen, low cost manufacturing may be the key to long term success. Japanese makers may be at a disadvantage with their high labor cost and high infrastructure costs.

South Korean and Taiwanese manufacturers are closely following their Japanese counterparts in LCD developments, with mass production of LCDs imminent. Samsung Electronics Co., with nearly $15 billion in sales, introduced four types of TFT color LCDs ranging from 7-inch to 10-inch displays at Japan's LCD International exhibition in September, 1994. Samsung's engineers had frequently visited NEC's Kagoshima Plan to master the quality levels of all raw materials and components supplied from NEC. Production tests at Samsung's plant on the outskirts of Seoul were scheduled to begin by the end of 1994. The facility was to have capacity to produce 100,000 10-inch displays per month. Initial production of 40,000 displays per month would be available by March, 1995. Samsung's price for a 9-inch TFT LCD was expected to be around $500. The current price for a 9-inch TFT-LCD panel was under $900 and $450 for STN panels. The senior managing director for Tottori Sanyo projected the cost of STN panels to reach $400 by early 1995. The prices were expected to fall to $500 and $300 by late 1995.

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[9]Op. cit. *Display Devices*, Spring 1994, pp. 12-13.

Goldstar Co., with $6 billion in sales, planned initial production capacity of 40,000 10-inch displays per month. Its Pusan LCD plant would begin in September, 1995, with initial production of 20,000 displays per month. Each company invested over $400 million in LCD production in 1993, nearly double either Sharp or NEC investments. Goldstar planned to invest over $620 million in its new plant to produce one million 10-inch displays annually by 1997. Using 90 percent Japanese equipment and materials, generous government funding and strategic alliances, Korean conglomerates were gearing up for an export offensive. And as the drive continues to develop larger and cheaper screens, industry analysts say Japan's continued dominance is far from assured. According to Goldstar vice chairman Lee Hun-jo:

> We are totally focused on one goal -- to develop a national industry that holds a prominent position in the global market, as we do with semiconductors. As for Goldstar itself, we have set a goal of becoming one of the top five or six firms in LCD production by the year 2000.[10]

The most important issue for Korean LCD production was to develop technologies to manufacture the production equipment and parts to meet their needs. Seoul is spending $156 million in an equipment development program that started in 1993 and will run until 1998. Goldstar teamed up with Alps Electric Co., a faltering Japanese electronics parts maker, to develop TFT-LCD technology and its manufacturing equipment. The ultra-clean technology developed in conjunction with Tohoku University will be the key to the Alps-Gold Star 50-50 joint venture. It was essential to reduce impurities to improve TFT-LCD production yields which were still relatively low. According to Alps' president Masataka Kataoka, "By developing new manufacturing technology, we might produce flat panels in Japan. Having invested in LCDs, Alps failed to come up with commercially competitive flat panels. Analysts estimated the investment in the joint project to cost over $100 million.

While U.S. firms work to develop the next breakthrough technology, South Korean and Taiwanese manufacturers are trying to catch up with Japan as they did in semiconductors.[11] Samsung and Goldstar planned to export 60%-70% of their displays to U.S. makers of notebook-type PCs. Both were negotiating contracts to supply TFT-LCDs to U.S. PC makers, such as Compaq and IBM, beginning in March of 1995. Since Compaq and other U.S. PC makers did not have an in-house source of LCD displays like NEC or Toshiba, they were seeking new suppliers.

The largest business group in Taiwan, Formosa Plastics Group, recently began production of LCDs and DRAMs. After a $44 million investment, it was targeting production of 10-inch STN-LCD panels for notebook PCs. The company, a leading producer of computers and motherboards in Taiwan, planned to reach monthly LCD sales of $120 million by March, 1996. Data International Co., Ltd. also manufactured and

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[10] *Business Week*.

[11] Samsung announced the development of the world's first 256-megabit dynamic random-access memory chip in August, 1994. Production was expected to begin in 1997. Korea expects to export over $12 billion worth of semiconductors in 1994.

supplied small LCD modules worth $11 million in sales by 1993. By February, 1995, the company planned to begin LCD module assembly in China to increase monthly production from 180,000 units to 350,000 units. Taiwan sales accounted for 25 percent of output and 75 percent was exported, with 45 percent of exports going to the U.S., 35 percent to Asia, and 20 percent to Europe.

Merck of Germany, a chemical and pharmaceutical group, recently purchased a 10 percent stake in Philips Consumer Electronics' flat display panel subsidiary. Merck produces materials used in the manufacture of LCDs. After the sale, Philips held 70 percent, with Merck, Thomson Microelectronics and Sagem of France owning 10 percent each. Demand for TFT displays in Europe continued to surpass supply, pushing prices to record levels. According to Data Modul, one of the largest European distributors of LCD displays, the continent still sourced 70 percent of its displays from Japan.

**The U.S. National Flat-Panel Display Initiative**

The barriers to entry in flat panel displays had resulted in the U.S. National Flat-Panel Display Initiative (NFPDI), a five-year, $587 million program to jump-start a commercial industrial base to meet future U.S. military needs. Despite a $300 million investment in pre-competitive flat-panel R&D by the department of defense's (DOD) advanced research projects agency (ARPA), no U.S. company had moved into high volume production. An active-matrix LCD plant with enough capacity to serve a volume market would cost about $400 million.[12] The final investment was estimated at two to three times that to develop sale and distribution systems. U.S. companies were also concerned about the availability of raw materials, components, and manufacturing equipment, which together accounted for 60-70 percent of manufacturing costs. According to Kenneth Flamm, deputy assistant secretary of DOD, this had become a national security problem:

> Flat-panel displays are not only needed for future battlefields but also to update the outmoded technology of today. Current aircraft cockpits, for example, contain rows and rows of little dials that convey information in an indigestible fashion. Flat-panel displays make it possible to integrate all this imaging and sensor data and present it on large, simple screens. DOD studies using simulated combat engagements show that solely as a result of having a large tactical-situation display available, the combat kill-ratio for F-15 fighter pilots goes up by about 30 percent. Displays mounted in the helmets of tank and helicopter crews promise similar results.[13]

To meet DOD requirements, military operations needed early access to prototypes of new products to determine military utility, assured access to custom products using the latest advanced commercialized technologies, and affordable displays for wide-spread deployment. Flamm continued:

> Why can't we rely on our Japanese allies for these products? A major reason is that a significant defense "allergy" exists in Japan. Companies there simply want nothing to do with any military business. Executives at Sharp, the market and technology leader, made it clear to us early on that they would not sell to us directly and that they would not customize products for DOD. We did not even get to consider the question of whether access to prototypes was possible. Since suppliers will need to incorporate proprietary and sometimes even classified technology into the

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[12] The price tag on a high volume semiconductor factory now approached $1 billion.

[13] Kenneth S. Flamm, "Flat-Panel Displays: Catalyzing a U.S. Industry," Issues in Science and Technology, Fall 1994, p. 28

displays, a relationship of trust is essential. We just did not see that happening without some fundamental changes in attitudes.[14]

The NFPDI approach was to invest more in core R&D programs and infrastructure, to form R&D partnerships with companies that commit to production, and to stimulate demand. Core R&D investments will amount to $318 million over five years, $50 million for the manufacturing tested, and $199 million in R&D incentives tied to production, and $20 million in purchase incentives. Since industry matching was required, the total investment over five years was expected to exceed $1.2 billion. The resulting U.S. display consortium, a collaborative group of government and private organizations that promotes development of flat panel display, consists of 14 companies and organizations, including ARPA and AT&T. Malcolm Thompson, president of the consortium, sees standardizing substrates as essential for growth in the flat panel display industry and emphasized the need to adapt new technologies to mass production.

**Suppliers to the Industry**

The Semiconductor Equipment Association of Japan indicated that equipment shipments for LCD manufacturing increased 53 percent in 1993, to $528 million. Shipments for 1994 were projected at $1 billion. As Sharp, NEC and other major LCD makers planned huge capital investments, the makers of LCD production machinery were feeling the pressure. The LCD industry was supported by a relatively small number of manufacturers of semiconductor production equipment that wanted to hedge their risks against silicon cycles. These small makers had limited capital, a limited number of engineers, and limited production capacity. They had become a critical bottleneck for an industry that expected to double its output in the near future.

For each step in the production process shown in Figure 10, there were an average of 1.5 makers of process equipment in Japan. Large and continuous rush orders from Japanese customers as well as from Korean customers were piling up on this oligopolistic industry. The equipment makers were ultimately determining the growth of the industry. Asao Ueno, president of Japan Vacuum Technology, Inc. (JVT), kept getting pleading phone calls from large LCD makers saying, “Please, we must have two additional pieces of equipment by next February 21. We must.” With a market share of 60 to 70 percent, JVT was the largest maker of sputtering equipment for LCDs, the equipment that forms fine films of electrodes on the glass substrate. The company expected to make $200 million of sputtering equipment sales during fiscal year 1994. It had forecast only $120 million in sales at the beginning of the year. To meet growing demand, JVT organized a back-up production team composed of its major manufacturing subsidiary in Kagoshima, Fuji Susono, and Tohoku Shinku Gijutsu; producers of semiconductor production machinery and other industrial equipment.[15]

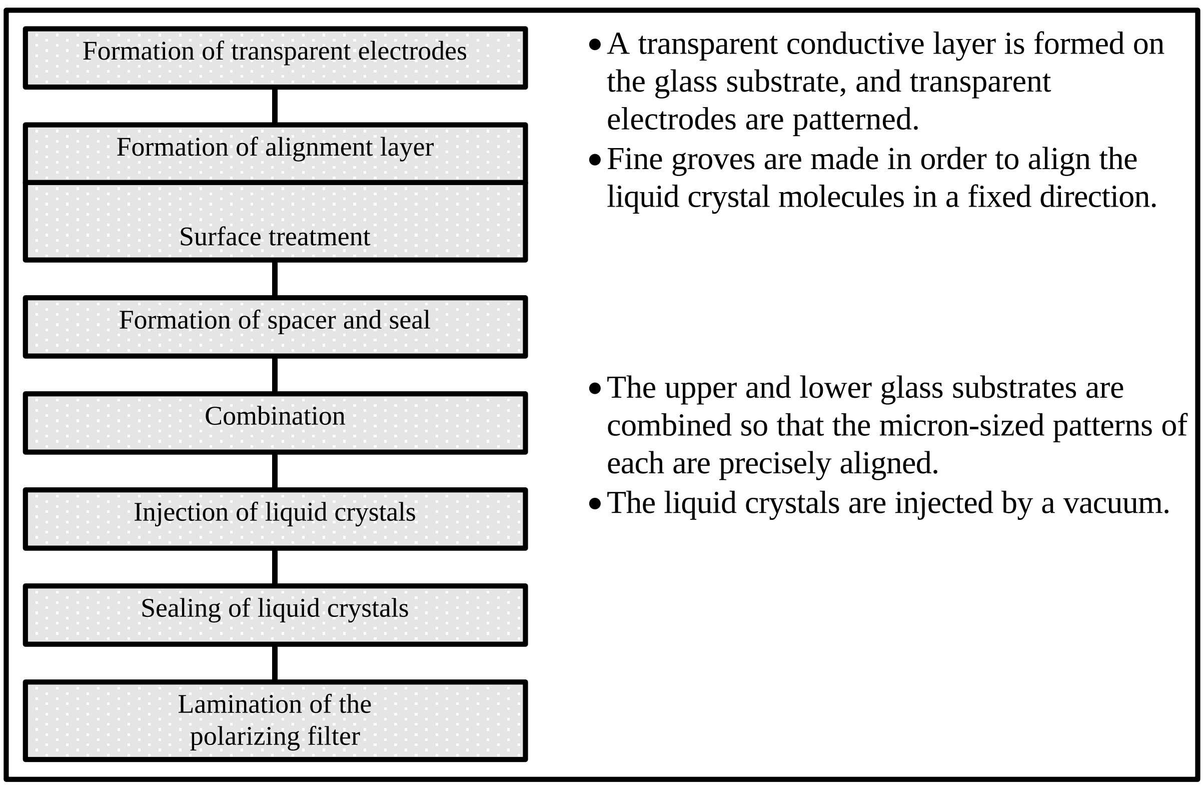
NEC Anerva held 50 percent of the market for plasma CVD equipment for thin film transistors. This company was in a similar position to JVT and was planning to

[14] Op. cit.
[15] Nikkei Sangyo newspaper series on the LCD industry, September 16-19, 1994.

relocate its production line in a larger plant where more space was available for clean room operations. But while equipment sales were brisk, suppliers had no way of predicting future demand. LCD demand was strong while semiconductor demand was picking up again. With U.S. PC sales growing, five Japanese semiconductor makers had planned to invest $5 billion on semiconductor plants. But equipment makers have been burnt before with drops in semiconductor sales, and have been cautious to add capacity.

The shortage in raw materials was resolved recently, but continued strong demand was still a concern. Price competition in the PC market was putting pressure on LCD makers to reduce costs. The shipping price of a 10-inch TFT-LCD panel was expected to fall to $500 by 1996. They were making demands on raw material makers to also lower their prices. Liquid crystal materials were key. As shown in Figure 11, material makers blended dozens of liquid crystal compounds to meet user specifications. Due to a complicated patent network, only three makers handled the $100 million market for liquid crystal materials in Japan: Chisso (a joint venture between Dai Nippon Printing Co. and LaRoche Japan) with 40 percent of the market, LeRoche with 30 percent, and Merck of Germany with 20 percent. Kenjiro Shoji, director of Chisso, felt that the cost reduction pressure of LCD makers was so strong that suppliers had difficulty paying for their development expenses. While LCD sales were growing, there was virtually no growth in shipments of liquid crystal materials due to the growing efficiency of production equipment. Competition remained severe.

**Figure 10: Liquid Crystal Cell Production Process**



For TFT color LCDs, the cost of color filters were around $100, between 10 and 15 percent of the total display cost. Color filters were also in shortest supply. Color filters are made of glass panels on which a lattice pattern of red, blue, and green colors are printed in microscopic precision. Because each rectangle must correspond to each pixel, high level mass production technology is required in color filter production. Because supply of color filters could not meet the high growth of LCD demand, this was a major bottleneck.

Capacity expansion plans for color filter production was about to double. Toppon Printing was increasing capacity by 50 percent to 600,000 10-inch panels per month by mid 1995. Dai Nippon Printing, the second largest maker, was increasing capacity to 250,000 panels per month by the end of 1994. Sanyo and Fujitsu were planning in-house production of color panels. Sumitomo Chemical had already announced plans to enter the market.

**Figure 11: Liquid Crystal Material Blends**

| Liquid crystal material (base material) |
|---|
| • Esters<br>• Biphenyl's<br>• PCH compounds (phenylcyclohexanes)<br>• Cyclohexanes<br>• Phenylpyridines<br>• Dioxane |

| Material Blends | | |
|---|---|---|
| Desired property | Objective | Liquid crystal materials blended |
| ① Voltage | Decrease drive voltage (for battery drive, etc.). | • P-esters<br>• N-esters |
| ② Temperature | • Withstand high temperature environments.<br>• Broaden stable operating temperature range (automobiles, aircraft, trains, etc.). | • Tricylic compounds<br>• Tetracylic compounds (withstands high temperatures) |
| ③ Viscosity | Improve response (for moving images, etc.) | • PCH compounds |
| ④ Refractive index | Match with the color to obtain the brightest white. | • PCH compounds (small refractive index)<br>• Biphenyl compounds (large refractive index) |
| ⑤Elasticity | Improve rise characteristic when voltage is applied (results in high contrast). | Depends on base material.) |